LOW ALPHA OPERATION OF THE MLS ELECTRON STORAGE RING

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Abstract

There is an increasing interest in Pico and sub-Pico second long bunches in electron storage rings [1]. These bunches can be achieved by tuning the ring into a dedicated 'low-α' optics [2]. A key parameter to control the bunch length is the momentum compaction factor α. The Metrology Light Source (MLS) [3] of the PTB (Physikalisch-Technische Bundesanstalt, the German national metrology institute) is the first storage ring, which applies a new method for reliable tuning of the low-α optics, based on a sextupole and octupole correction scheme [4]. With this method, α can be varied by more than a factor of 1000 and stable beam storage at low-α values is achieved. We present here the first operating results of the low-α optics. Characterizations of related THz radiation at MLS are presented in [5].

THE MLS OPTICS

The MLS lattice is a 4 cell double bend achromat structure with alternating long and short straight sections. The main parameters of the ring are listed in Tab.1. The beam is injected from a 105 MeV microtron and ramped to max. 630 MeV. Optical functions of the user and low-α optics

Table 1: Main MLS Parameters

parameter	value
injection energy	105 MeV
max. energy	630 MeV
circumference	48 m
optics	4 cell double bend
rf-frequency	500 MHz
max. rf-voltage	500 kV
hor. / vert. tune	3.2 / 2.2
short / long straigth	2.5 m / 6 m
rms-bunch length	5 mm to 0.5 mm

are compared in Fig. 1. For the low-α optics it is seen, that the dispersion function D is forced to do a zero crossing inside the dipoles.

Beside other tasks, the MLS design is optimized for easy tuning of the low-α optics. To operate the low-α mode, the beam is first injected and ramped to the desired energy by applying the normal user optics. Then a sequence of 5 optics files of different magnet settings is loaded into the machine, to stepwise reduce α to the desired value. These

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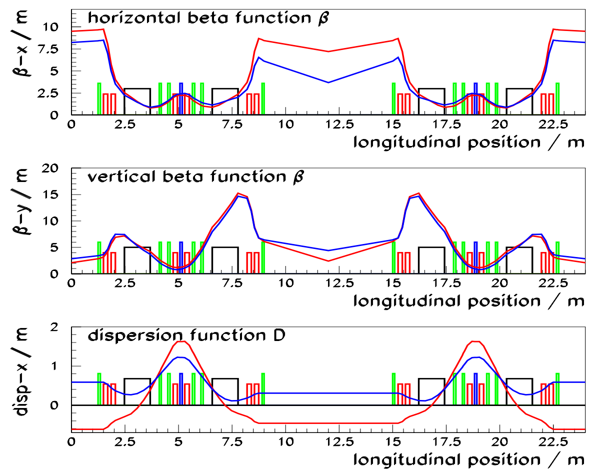

Figure 1: Optical functions of the user optics (blue line) and the $\alpha = 0$ optics (red line). Half of the ring is displayed. Magnetic multipoles are indicated by coloured boxes, dipoles (black), quadrupoles (red), sextupoles (green), octupoles (blue).

files are set up for a fixed transverse working point, small chromaticities and specified beam energy.

THE LOW-α OPTICS

Nonlinear α Terms

The relative change of the circumference $\Delta L/L_0 = (L - L_0)/L_0$ of a particle orbit around the storage ring as a function of momentum deviation $\delta = (p - p_0)/p_0$ defines the momentum compaction factor α as [6]

$$\Delta L/L_0 \quad = \quad \alpha\delta, \qquad (1)$$

where amplitude dependent terms can be neglected, if the transverse chromaticity is small [7]. Alpha is then considered as a function of δ and is expanded as

$$\alpha \quad = \quad \alpha_0 + \alpha_1\delta + \alpha_2\delta^2 .... \qquad (2)$$

Well designed low-α optics require the control of the momentum dependent synchrotron oscillation frequency f_s, which is approximately achieved by tuning the three leading α-terms. By tuning the dispersion function D inside the dipoles of bending radius ρ by quadrupoles, α_0 can be controlled and is given as $\alpha_0 =< D/\rho >$. The longitudinal chromaticity, $\xi_s = (\partial f_s/\partial\delta)/f_{rf}$ at δ=0, has to be controlled by changing α_1 independent of the transverse chromaticities using three well placed sextupole families. Further more, the curvature of α, given by α_2, is controlled by suitably placed octupoles.

For the design of the MLS ring, computer simulations with MAD [8] were performed to optimize the location and strength of these correction elements [4]. It was found, that one octupole family is sufficient and could be placed in the centre of the achromat, at maximum dispersion, see Fig. 1 (this tuning scheme was then adopted by the ALS, Berkeley (USA), for the CIRCE proposal of a coherent light source). The octupoles are relatively weak. They have a maximum pole tip field of 0.03 T at 40 mm radius and a mechanical length of 80 mm.

The momentum compaction factor as a function of the quadrupole 'q1' (inside the achromat) excitation current is shown in Fig. 2 (left), where α_0 is derived by scaling the measured f_s value, $\alpha_0 \propto \sqrt{f_s}$. The value α_0=0.033 of the user optics, derived from optics codes, is used to adjust the data. Presently, a current of about 100 mA with few hours life time can be stored in the low-α optics at 630 MeV, 450 MeV or 350 MeV.

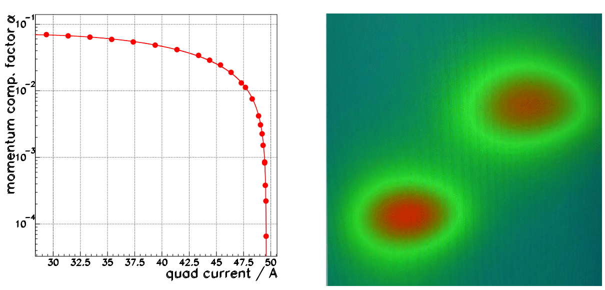

Figure 2: Left: The low-α tuning range ($\alpha_0 > 0$) of the MLS at 630 MeV as a function of the quadrupole 'q1' current (dots). The trend line is a parabolic fit to the data. Right: If α_0 becomes < 0 the beam splits into a stable pair of α-buckets, visible on a synchrotron radiation monitor.

Beam dynamical calculation are often performed for α independent on δ. At small values of $|\alpha_0|$ these results need to be modified by higher order terms of α. If α_0 and likewise f_s becomes small, particles could approach the $f_s = 0$ resonance and are lost. To avoid these complications, f_s should be independent of momentum, i.e. ξ_s= 0. It would be even better, to control higher order terms of α in such a way, that off energy particles show a larger oscillation frequency f_s, this is achievable if $\alpha_1 = 0$ and $\alpha_2 > 0$.

Figure 3 (left) shows measurements of f_s as a function of the change in rf-frequency, Δf_{rf}. As predicted, the MLS optics can be tuned to ξ_s=0 by the sextupoles and the octupoles control the curvature of f_s with respect to Δf_{rf}. At f_{s0}=4kHz there is still a residual positive curvature visible, even if the octupole are switched off.

The variables $(f_s, \Delta f_{rf})$ are very convenient for machine low-α tuning. The frequency f_s can be monitored online at different α values by means of a spectrum analyzer. These variables can be transformed into (α,δ) [9], as

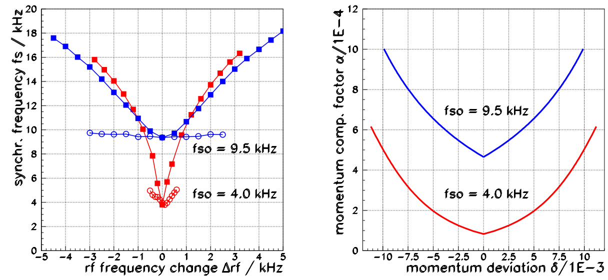

Figure 3: Left: Synchrotron frequency f_s as a function of the rf-frequency change Δf_{rf} for two different sets of α, $\alpha_0 = 8.25E-5$ and $\alpha_0 = 4.6E-4$. The circles show measurements with octupole 'off', the square data with octupole 'on'. Right: Nonlinear α as a function of momentum deviation δ. Both Figures apply the data with octupoles 'on'.

shown in Fig. 3 (right), better suited for beam dynamics considerations. As a simple approximation $(f_s/f_{s0})^2$ can be fitted by a parabolic function

$$(f_s/f_{s0})^2 = 1 + A|r| + Br^2, \tag{3}$$

where $r = \Delta f_{rf}/f_{rf0}$, f_{rf0} the nominal rf-frequency and f_{s0} the synchrotron oscillation frequency at $r = 0$. The $|r|$ term could lead to the small kink at $r = 0$, see Fig. 3 (right). The results are A=3.82E6, B=-1.3353E11 and α_0=8.25E-5 for the f_s =4 kHz case and A=2.6748E5, B=6.3923E9 and α_0=4.6E-4 for f_s=9.5 kHz. A 4th order Taylor series expansion of α yields

$$\begin{aligned}\alpha &= \alpha_0 + \alpha_0^2 A|\delta|/2 \\ &\quad +\alpha_0^3(A^2+2B)\delta^2/6 \\ &\quad +\alpha_0^4 A(A^2+8B)|\delta|^3/24 \\ &\quad +\alpha_0^5(A^4+22A^2B+16B^2)\delta^4/120,\end{aligned} \tag{4}$$

where $|r| << 1$ is assumed. The expanded solution is in good agreement with the analytical solution of the parabolic fit function, plotted in Fig. 3 (right).

Low-α Buckets

Some basic properties of the longitudinal optics can be discussed if only two terms of α are applied, $\alpha = \alpha_0 + \alpha_2\delta^2$. The small amplitude Hamiltonian H of the variables (ϕ, δ) , where ϕ is the longitudinal phase position of the particle, can be approximately written as

$$H = H_0\phi^2/2 + 2\pi f_{rf}\int \alpha\delta d\delta, \tag{5}$$

with $H_0 = eV_{rf}/T_0cp_0$ and V_{rf} the rf-peak voltage, T_0 the revolution time, c the speed of light and p_0 the particle momentum. A positive H_0 is chosen to get stable fixed points at $\phi = 0$. The momentum slip factor η is approximated as $-\alpha$. The momentum related part of the fixed points δ_F are derived from $\partial H/\partial\delta$=0. They occur at $\delta_F = 0$ and $\delta_F^2 = -\alpha_0/\alpha_2$. If the expression $H_{\delta\delta} = \partial^2 H/\partial\delta^2 = 2\pi f_{rf}(\alpha_0 + 3\alpha_2\delta^2)$ taken at $\delta = \delta_F$ is positive, these fixed points are stable. For the first set with $\delta_F = 0$ we get $H_{\delta\delta} = 2\pi f_{rf}\alpha_0$ and stability if $\alpha_0 > 0$. For the second set with $\delta_F^2 = -\alpha_0/\alpha_2$ we get $H_{\delta\delta} = 4\pi f_{rf}\alpha_2\delta_F^2 = -4\pi f_{rf}\alpha_0$ and stability, if $\alpha_0 < 0$. Changing α_0 by an appropriate quadrupole tuning from positive to negative values moves the fixed points from $\delta_F = 0$ to $\delta_F = \pm\sqrt{-\alpha_0/\alpha_2}$ at stable beam storage. For a positive curvature of α, i.e. $\alpha_2 > 0$, the last case yields two stable fixed points. This tuning is easily performed at the MLS, where the beam can be shifted between a pair of 'α-buckets' and a single bucket back and forth without losses. An example of the α-buckets is shown in Fig. 2 (right). This demonstrates the tuning flexibility of the low-α optics, achieved by sextupole and octupole families.

The signal of f_s vanishes, if α_0 approches zero. At $\alpha_0 < 0$, the beam can populate two α-buckets and the f_s-signal, now one for each bucket, becomes visible again. During this transition the emitted coherent THz power was detected. It approaches first maximum intensity and decreases with the population of the two α-buckets.

From the harmonic potential solution of the synchrotron oscillation, expressions for bunch length σ and α_0 can be derived. For ultra short bunches these relations become limited by several effects. If nonlinear α terms become dominant, these relations needs to be modified [10]. Coupling between the transverse and longitudinal oscillation in dispersive sections influences the bunch length [11]. For the MLS optics it has been found by tracking calculations [12], that bunches of 0.1 ps length could be observed (without any other bunch lengthening effects taken into account) at special ring positions, dependent on the chromatic H-function. Additionally, trapped ions affect the beam dynamics [13] and become visible, e.g., when the ion clearing voltage is switched off, leading to 2 times stronger THz signals, see Fig. 4, emitted in the low-α optics.

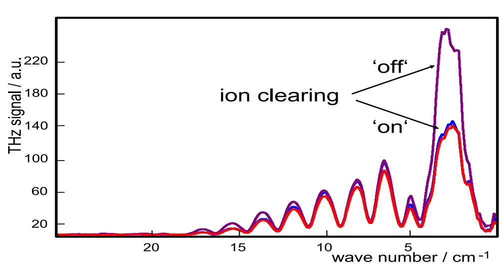

Figure 4: Detected Fourier-Transform THz spectrum with and without applied ion clearing voltage. The low frequency part of the spectrum doubles intensiy if the clearing voltage is switched off.

Beside a large tuning range of α, the MLS is the first storage ring equipped with a higher mode damped cavity [14]. A large tuning range of the rf-voltage from about 50 kV (the minimum required for beam storage at 630 MeV) to 500 kV is an additional tool for easy bunch length manipulation.

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